Adaptive Optics at the World's Biggest Optical Telescope

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ABSTRACT

The Large Binocular Telescope (LBT) on Mt. Graham, Arizona, comprises two 8.4 m primary mirrors on a common mount. The two apertures will be co-phased to create a single telescope with 110 m^2 of collecting area and 22.7 m baseline. From the outset, adaptive optics (AO) was incorporated into the design through two adaptive secondary mirrors (ASM), each 91 cm in diameter with 672 actuators, which feed all of the instruments mounted at the telescope's four pairs of Gregorian foci. The first ASM has now seen first light on sky with natural guide stars. Strehl ratios at 1.6 μm under average seeing are estimated to be ~80%, and diffraction-limited performance is maintained for stars down to magnitude 15. At the same time, pioneering work at the 6.5 m MMT telescope has for the first time shown the compelling benefits of ground-layer AO compensation. This technique relies on the signals from multiple laser beacons to sense and correct aberration arising close to the telescope with the result that near IR seeing is reduced by a factor of 2-3 over a field of many arc minutes. Building on these efforts at both telescopes, a project is underway to enhance the LBT's AO capability by the addition of wavefront sensing with multiple laser guide stars. The Advanced Rayleigh Ground-layer adaptive Optics System (ARGOS) is now in the construction phase. We provide an overview of ARGOS and how it foreshadows AO systems destined for the 30 m class telescopes of tomorrow.

1. OVERVIEW OF THE LARGE BINOCULAR TELESCOPE AND ITS AO SYSTEMS

The LBT, shown in Fig. 1, has been constructed by an international consortium with partners from the US, Germany and Italy [1]. It is now the largest optical/infrared telescope in the world, with a collecting area of 110 m^2, and for this and other reasons offers uniquely powerful scientific capabilities. In particular the 22.7 m baseline provided by the two primary mirrors, when co-phased, will offer the highest spatial resolution for studies of faint objects that makes the LBT arguably the forerunner of the next generation of Extremely Large Telescopes (ELTs). In this mode, light from the two apertures is combined as in a Fizeau interferometer, meaning that light arrives at the *combined* focal plane in exactly the same way as it would from a single 22.7 m aperture masked with two 8.4 m holes. In this way, the full resolution of the 22.7 m baseline is achieved over the entire field of view (FOV), which cannot be done with conventional multi-aperture interferometers such as the Navy Prototype Optical Interferometer [2] or the combination of the two Keck telescopes [3], where the apertures are on separate mounts.

In common with other large telescopes around the world, the LBT relies on adaptive optics (AO) to deliver high resolution imaging and spectroscopy. In fact the LBT was designed from the outset to include AO as an integral part of the telescope; no other telescope has ever been built this way. On the other hand, the LBT is unique among telescopes of 8 m and above in that the AO correction is built in to the telescope's secondary mirrors. This capability allows for correction of all instruments used at the Gregorian foci, without any requirement for relay optics that introduce losses and increase thermal background, complexity, and cost.

First-light AO relies on natural guide stars (NGS), with atmospheric aberration measured by pyramid wavefront sensors [4]. We present first results in this paper. To expand the reach of its AO systems, the LBT Observatory has in addition launched a phased program to augment the telescope with laser-guided capability. Phase I, called the Advanced Rayleigh Ground layer adaptive Optics System (ARGOS) is now under construction [5]. It will deploy six low-level Rayleigh laser guide stars (LGS), three per aperture, to correct low-lying turbulence, which is isoplanatic over a wide FOV. This ground-layer adaptive optics (GLAO) mode of operation will deliver images in the near infrared that routinely reach ~ 0.2–0.3 arc sec resolution over a 4 arc min FOV. The Phase I system is on track for deployment as a facility system in early 2012.

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14. ABSTRACT
The Large Binocular Telescope (LBT) on Mt. Graham, Arizona, comprises two 8.4 m primary mirrors on a common mount. The two apertures will be co-phased to create a single telescope with 110 m2 of collecting area and 22.7 m baseline. From the outset, adaptive optics (AO) was incorporated into the design through two adaptive secondary mirrors (ASM), each 91 cm in diameter with 672 actuators, which feed all of the instruments mounted at the telescope's four pairs of Gregorian foci. The first ASM has now seen first light on sky with natural guide stars. Strehl ratios at 1.6 μm under average seeing are estimated to be ~80%, and diffraction-limited performance is maintained for stars down to magnitude 15. At the same time, pioneering work at the 6.5 m MMT telescope has for the first time shown the compelling benefits of ground-layer AO compensation. This technique relies on the signals from multiple laser beacons to sense and correct aberration arising close to the telescope with the result that near IR seeing is reduced by a factor of 2-3 over a field of many arc minutes. Building on these efforts at both telescopes, a project is underway to enhance the LBT's AO capability by the addition of wavefront sensing with multiple laser guide stars. The Advanced Rayleigh Ground-layer adaptive Optics System (ARGOS) is now in the construction phase. We provide an overview of ARGOS and how it foreshadows AO systems destined for the 30 m class telescopes of tomorrow.

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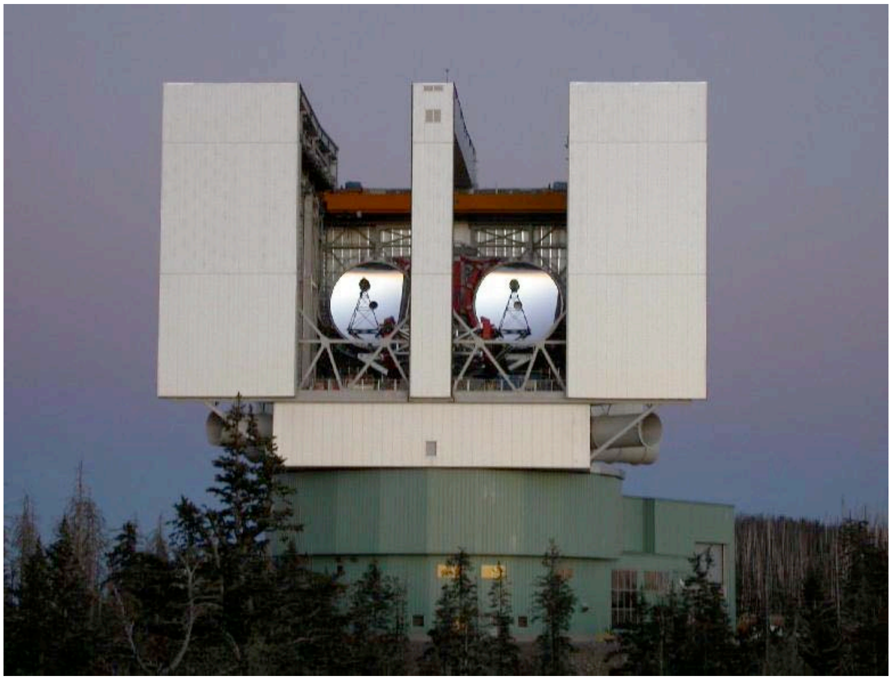


Fig. 1. The Large Binocular Telescope on Mt. Graham, AZ comprises two unit telescopes on a single mount. Each primary mirror is 8.4 m in diameter, and the two unit telescopes can be combined to produce images *exactly* as would be seen from a *single* 23 m aperture masked with two 8.4 m holes.

Phase II is to be developed in parallel. A sodium LGS and additional wavefront sensor (WFS) will be added to each aperture using the same launch optics as the Rayleigh beacons. AO feedback will be to the ASMs. Instruments will then enjoy images sharpened to the diffraction limit of the individual 8.4 m apertures in the near IR wavebands. In future, Phase III will combine use of the low-altitude Rayleigh and high-altitude sodium LGS into a unique tomographic wavefront sensing system for multi-conjugate adaptive optics (MCAO).

Truly ground-breaking, however, will be the implementation of AO correction for the LBT Interferometer (LBTI) [6]. This instrument implements a number of near, mid, and long-wave IR cameras at the telescope's combined focus. Imaging will be available with the full resolving power of the LBT at wavelengths from 2 to 20 μm, and with unique sensitivity in the thermal bands because of the minimal number of warm optics in the beam. High-quality AO control of the individual apertures will be provided by the ASMs, with piston control between the apertures provided by a fringe tracker operating at 2 μm, already built into the instrument. In addition to its standard Fizeau configuration, LBTI can be configured to operate as a Bracewell nulling interferometer, for which the laser AO will allow high-contrast investigation in the thermal IR of the environments of deeply embedded stars that are very faint in the optical.

1.1 Making the Primary Mirrors at the Steward Observatory Mirror Lab

The primary mirrors for the LBT were made at the Steward Observatory Mirror Lab, a facility of the University of Arizona. Starting from blocks of Ohara E6 borosilicate glass ~10 cm on a side, the glass is melted in a furnace (Fig. 2) that rotates to give the surface of the melt the desired concave parabolic shape for the final mirror. A ceramic fiber mold inside the furnace defines a hollow-core ribbed structure around which the molten glass flows. After the blank cools to room temperature, it is lifted from the furnace, and the mold material removed out of holes in the back plate of the blank. In this way, a very rigid mirror is formed, about 1 m thick at the outer edge, but with only 20% the weight of an equivalent solid blank.

Loose-abrasive grinding of the back surface of the blank ensures removal of all minor cracks that might propagate over the lifetime of the mirror. The front surface is also ground, using a stressed-lap tool seen in Fig. 3. This is a 1.5 m diameter plate whose shape can be changed in real time under computer control to match the desired local

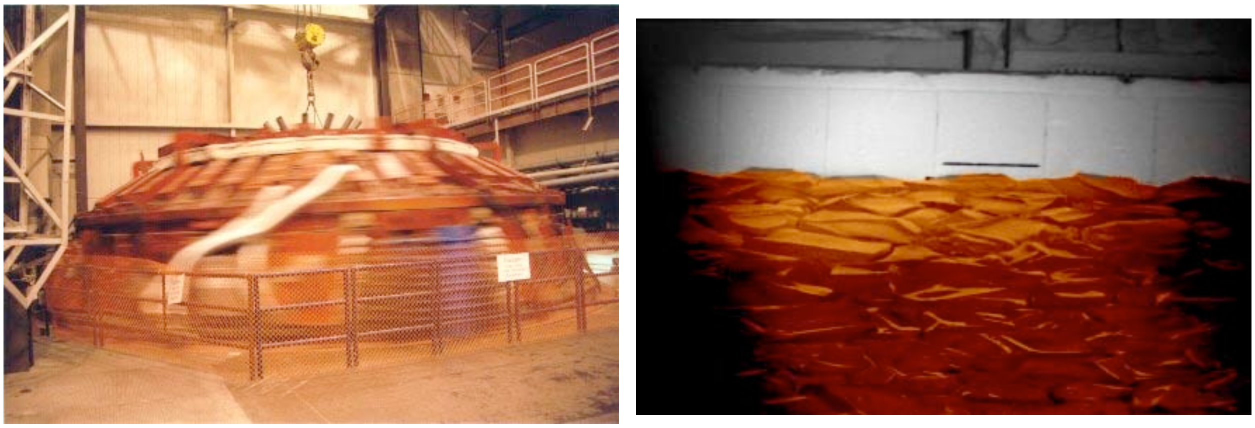


Fig. 2. The LBT's primary mirrors were made from scratch in the Steward Observatory Mirror Laboratory on the campus of the University of Arizona. (*Left*) The spinning furnace in which the blanks are cast rotates 6-8 times per minute to impart the desired parabolic shape to the liquid glass. (*Right*) Inside the furnace, individual blocks of glass are heated to 1190°C, at which point they melt to the consistency of honey, flow down into the mold, and form the blank.

Fig. 3. (*Left*) One of the LBT mirrors being polished with a dynamical stressed lap technique developed at the Mirror Lab. (*Right*) In the casting facility, three large blanks await grinding and polishing; from front to rear, the two 8.4 m LBT mirrors face down, and a 6.5 m mirror still sitting face up on the furnace turntable, with the steel lifting fixture attached.

curvature of the highly aspheric surface. Finally, the mirror surface is polished using the same stressed lap tool to an accuracy of ~15 nm rms.

2. ADAPTIVE OPTICS AT THE LBT

High-order AO compensation is now *de rigueur* for large general-purpose astronomical telescopes, with a general expectation that over modest fields of view, diffraction-limited imaging will be available in at least the near IR bands from 1.2–2.5 μm. The LBT was designed from the outset to include AO as an integral part of the telescope, and to that end the telescope is being equipped with a pair of ASMs of the same construction as the ASM built for

the 6.5 m MMT [7]. The adoption of ASMs enables AO in the thermal infrared, at wavelengths > 2.2 μm, with the highest signal-to-noise ratio (SNR) by minimizing thermal background radiation from the optics themselves. In addition, because the ASMs are large, 91 cm in diameter, a high étendue is preserved, allowing a wide corrected FOV which is to be exploited by the ground-layer AO mode of operation. As of this writing, the first of the two ASMs has been installed, and demonstrated with NGS; results are presented below.

The ASMs will be driven by wavefront sensors using both natural stars and laser beacons. Table 1 presents an overview of the range of AO systems that are being installed on the LBT, and the dates by which they are expected to be operational.

AO mode	**Implementation Date**
Natural guide star LBT 1	Now
Natural guide star LBT 2	Sept. 2011
Natural guide star co-phased	Dec. 2011
Wide-field ground-layer multi-laser-guided	Feb. 2012
Tomography, hybrid LGS, multi-conjugate	Early 2014

Table 1. Overview of AO operating modes and expected dates for availability.

2.1 Adaptive Secondary Mirror Construction

In addition to supporting the usual functionality of a secondary mirror, each of the two ASMs on the LBT provides high-order wavefront correction as well as control of fast tip-tilt errors, whether introduced by the atmosphere, vibration, tracking error, or mount jitter. The key components of an ASM are shown in Fig. 4, described here from the bottom up. The reflective, and deformable, component of each of the LBT's mirrors is a concave Zerodur shell, 1.6 mm in average thickness and 911 mm in diameter. The front surface is an ellipsoid; the back surface is spherical and supports 672 voice-coil actuators. The only physical connection between the shell and the rest of the telescope is via a central steel membrane which constrains torsional and in-plane motions of the shell, but allows tip-tilt and longitudinal translation.

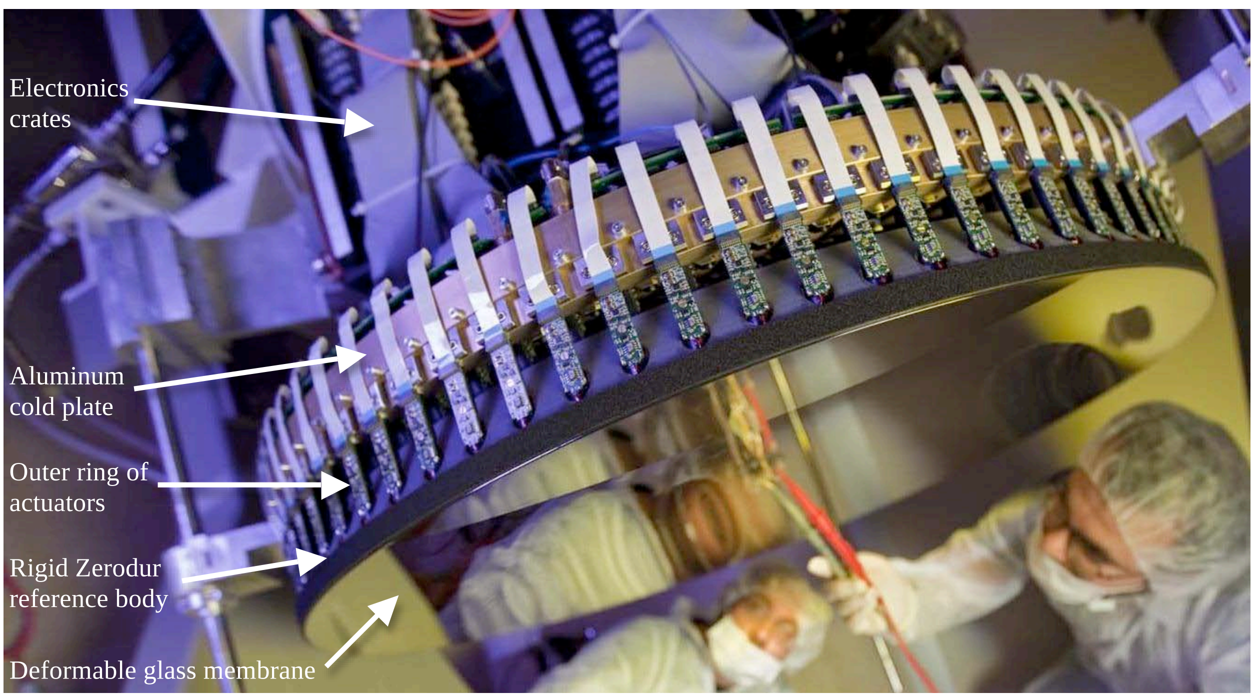


Fig. 4. The first ASM for the LBT, undergoing final tests at Arcetri Observatory in Florence.

Above the shell is a thick, stiff plate of Zerodur with front surface curvature matched to the back surface of the shell. Capacitive sensors collocated with the actuators sense the local displacement of the ASM in real time. The actuators themselves protrude through holes in the Zerodur and are attached to an aluminum "cold plate", a heat sink through which run coolant pipes that remove approximately 1 kW of heat dissipated by the ASM. The superstructure above these components supports three crates containing the real-time control electronics, with sustained computational rate of 163 Gflop. These both perform the wavefront reconstruction from the WFS signals and drive the 672 actuators by reference to the feedback provided by the capacitive sensors.

Because of the local nature of the ASM control system, the mirrors are equally agile in tip-tilt and modes of high spatial frequency. The 10–90% response time in all cases is < 1 ms, with slightly under-damped step response leading to 8% overshoot.

2.2 Pyramid Wavefront Sensors

The LBT is also unique in being the only large telescope equipped with pyramid wavefront sensors (PWFS) [4]. The PWFS gives essentially the same information as the Shack-Hartmann sensors that are used almost universally in AO systems deployed today, namely local wavefront slopes; but Guyon [8] has shown that when used with NGS that share the image sharpening of the AO system, the PWFS is fundamentally more sensitive to low-order wavefront aberration. In the LBT system, the PWFS is fed by starlight shortward of 1 μm wavelength, reflected off the entrance window of the science instrument. This is a dichroic beam splitter which also transmits longer wavelengths to the science focal plane.

The sensor itself is an E2V CCD39 with 80×80 pixels. The native format supports a maximum subaperture density of 30×30 across each 8.4 m pupil. The detector may be binned by factors between 2 and 8 to obtain fewer and larger subapertures, down to 4×4, to allow for the faintest guide stars.

3. RESULTS WITH THE FIRST NATURAL GUIDE STAR SYSTEM

The first of the telescope's ASMs was installed in May 2010. Full details are given in Reference [9]. On-sky tests began on the night of May 25, and the system immediately demonstrated performance comparable to the best astronomical systems now in operation. An example, recorded with the system's IR test camera, is shown in Fig. 5.

Fig. 6 shows a high Strehl ratio image of a bright star recorded at 1.6 μm. Although composed of many consecutive short exposures to overcome the limited bit depth of the camera, the total exposure time represented is 20 s; the individual images were simply added together with no recentering. (Note that the image is displayed here on a severe logarithmic stretch that completely saturates the central core in order to show extended details.) The AO system in this case was operating at 1 kHz update rate, driving 400 modes of correction. A number of features of this image are worth pointing out. Firstly, the Strehl ratio is estimated to be 80%, very high for an image at this wavelength with an aperture as large as 8.4 m, particularly given the seeing of 0.9 arc sec (at 500 nm), which is

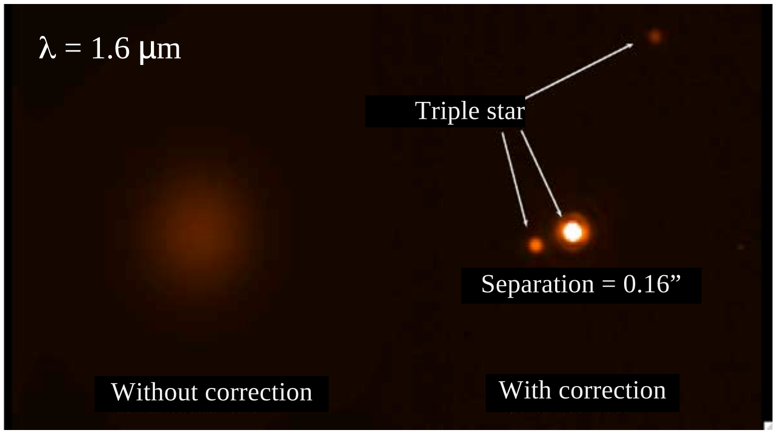


Fig. 5. NGS adaptive optics performance on LBT: 50%-80% long-exposure Strehl ratio is achieved in H band, illustrated here by the seeing limited image (*left*) and the adaptively corrected image (*right*).

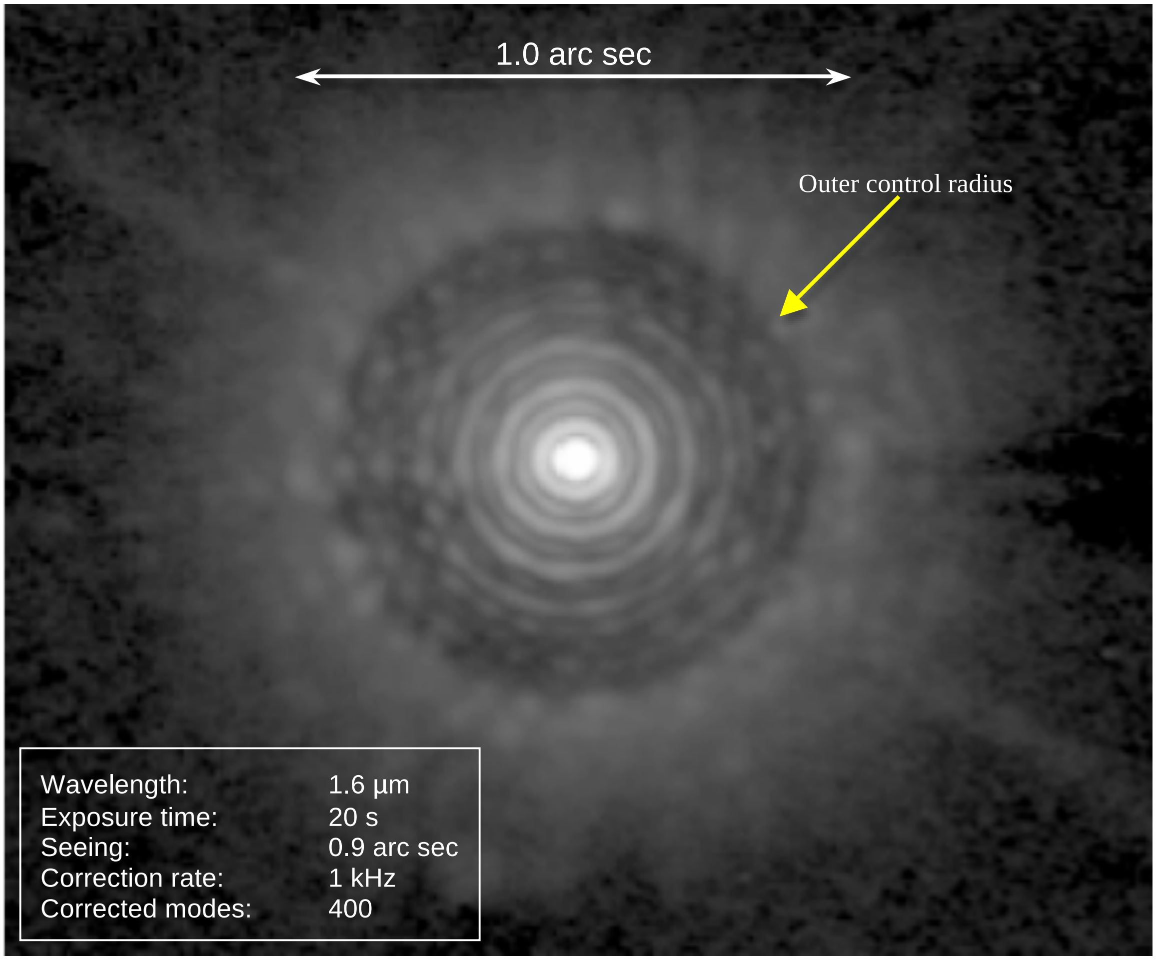


Fig. 6. AO stellar image of 20 s total exposure in H band showing multiple Airy rings inside the AO control radius (marked). The PSF halo outside this radius is attributable to wavefront aberrations of higher spatial frequency than were controlled by the AO system. The diagonal stripe from top left to bottom right is diffraction from the secondary support arm. The Strehl ratio is estimated at 80%. Log gray scale.

significantly worse than the mean value for the site of 0.67 arc sec. Surrounding the diffraction core, approximately 10 Airy rings can be distinguished. They do not diminish monotonically in brightness with radius, but rather alternate between brighter and darker, a feature characteristic of diffraction from a circular aperture with a central obscuration. Between the rings, the background illumination is very low. This region corresponds to spatial frequencies of the pupil-plane wavefront that are within the 400-mode spatial control bandwith of the AO system. The low background level is attributable to the excellent removal of power from the atmospheric aberration in these modes. Beyond the outer control radius of about 0.8 arc sec (marked in Fig. 6), the AO system has little traction, and the scattered light remains uncontrolled. Finally, the diagonal stripe across the PSF arises from diffraction at the single support arm which holds the secondary mirror above the primary (the LBT does not use conventional ‘spiders’).

Tests have been carried out to determine the degradation of performance with dimmer guide stars. In seeing of 0.6 arc sec, full performance with Strehl ratio > 80% is maintained for stars of R magnitude 12 (R being the band to which the PWFS is most sensitive). Strehl ratio of > 30% is preserved for stars as faint as 15th magnitude. This contrasts with the performance of systems based on Shack-Hartmann sensors which typically do not work well with stars fainter than about 12th magnitude; the ease with which the subaperture size may be redefined gives the PWFS a substantial advantage. In poorer seeing of 1.5 arc sec, the LBT system exhibits graceful performance degradation from Strehl ratio of 50% with an 8th magnitude star to 1% at about 15th magnitude.

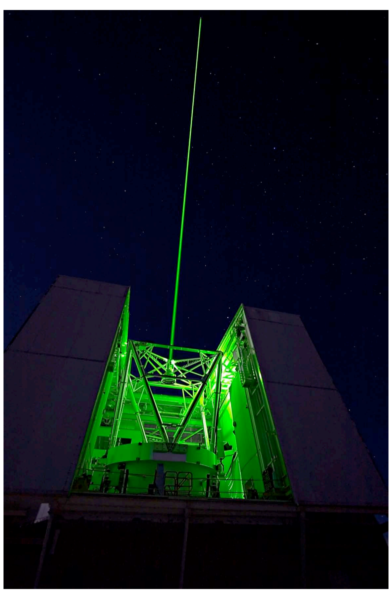
4. LASER-GUIDED ADAPTIVE OPTICS

While first-light AO relies on NGS, the LBT has launched a phased program to augment the telescope with laser-guided capability. Phase I, called the Advanced Rayleigh Ground layer adaptive Optics System (ARGOS) is now under construction for the telescope [5]. It will deploy six low-level Rayleigh laser guide stars (LGS), three per aperture, to correct low-lying turbulence, which is isoplanatic over a wide FOV. This ground-layer adaptive optics (GLAO) mode of operation will feed the 4 arc min wide-field modes of the LUCIFER near-IR imaging and multi-object spectrographic instruments with images that routinely reach ~0.2–0.3 arc sec resolution.

The Phase I system builds on our successful demonstration of GLAO at the MMT using a constellation of five Rayleigh LGS [10,11]. Fig. 7 shows the MMT with the beacons at 532 nm, and the beacons as they appear illuminating a layer of cloud. Typical results achieved with the MMT system are illustrated by Fig. 8, which shows two 60 s exposures of the core of the globular cluster M3 recorded at 2.2 μm wavelength, recorded with and without GLAO correction. Without correction, the stellar images reflect the native seeing of 0.7 arc sec. The second observation shows the image quality obtained with GLAO: the average image width across the entire field is reduced to 0.30 arc sec. Fig. 8b-e shows the results in two 27×27 arc sec regions of the field, one centered on the tip–tilt star and the other centered near the edge of the camera's field. Each subfield is about the size of the isoplanatic patch for conventional AO correction at this wavelength. We note that the point spread function (PSF) is nearly identical in the two subfields. Furthermore, the peak intensity of the stellar images was improved over the full field by an average factor of 3.4, which for a detection at a given signal-to-noise ratio leads to an improvement of 2 mag in this very crowded region. Although the correction does not reach the diffraction limit, which at this wavelength is 0.07 arc sec, the quality of the image improvement is essentially constant across the FOV.

In this instance, the corrected FOV is limited by the diameter of the beacon constellation, but we have made measurements that suggest a substantially wider field is possible [11]. LBT's ARGOS system employs the same method of multiple Rayleigh LGS to sense the ground-layer aberration, but will offer four times the FOV. It is on track for deployment as a facility system in mid 2012.

Phase II of the LGS implementation, which is in the planning phase, foresees the augmentation of the ARGOS system with two sodium laser beacons to offer all-sky imaging at the near-IR diffraction limit. The basic system design anticipates a guide star laser beam of 10 W above each eye of the LBT, with a final detected quantum efficiency at the WFS detectors of 40%. The WFS cameras will be identical for the LUCIFER and LBTI subsystems, and will put a 16×16 array of subapertures across each 8.4 m primary mirror.



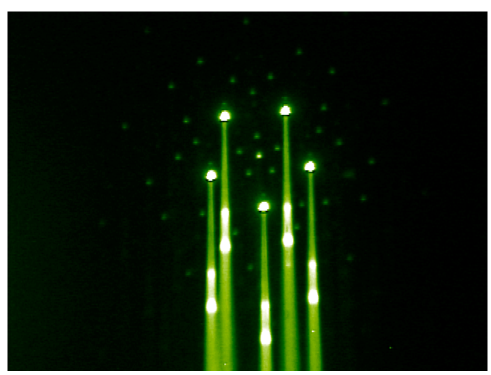


Fig. 7. (*Left*) Five laser beams, totaling 25 W at 532 nm, projected from behind the secondary mirror of the 6.5 m MMT telescope in southern Arizona. (*Right*) The beacons as they appear on the bottom of cloud. The pentagon spans 2 arc min. The 5 beams are made from a single beam using a computer generated hologram; this gives rise to additional diffracted spots containing a total of 20% of the power.

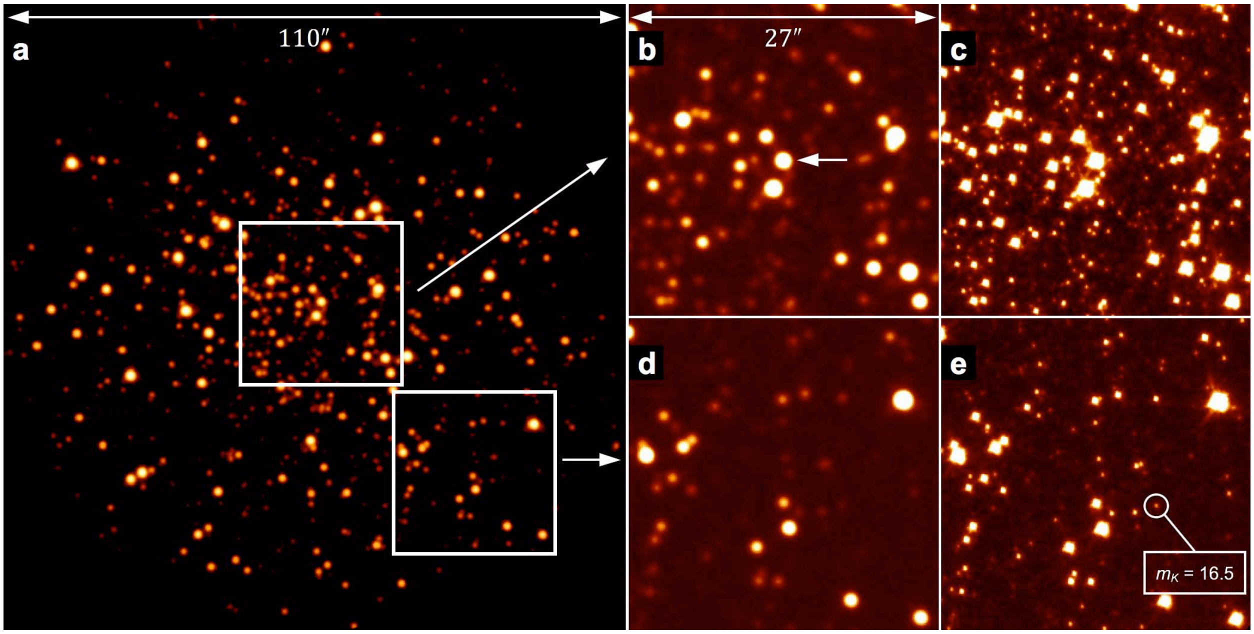


Fig. 8. The core of M3 imaged at 2.2 μm in two 60 s exposures. a) The full 110 arc sec field of the IR camera in the native seeing limit of 0.7 arc sec, on a logarithmic intensity scale. b,d) Two smaller 27 arc sec regions of the same image, indicated by the boxes in a) shown on a truncated linear scale in which bright stars appear saturated but which reaches the noise floor and brings out the faintest observable stars. c,e) In a second 60 s exposure of the same two regions, taken with GLAO running at 400 Hz and shown on the same linear scale as b) and d), the stellar image width is reduced to 0.3 arc sec and has a very similar PSF morphology across the whole field of view. For reference, we highlight a star in the corrected image with K band magnitude of 16.5, detected at a SNR of 26. In the uncorrected image, stars must be 2 mag brighter to be seen at the same SNR.

Finally, Phase III will combine use of the low-altitude Rayleigh and high-altitude sodium LGS into a uniquely powerful tomographic wavefront sensing system for multi-conjugate adaptive optics (MCAO). This hybrid sensing system will require just a single tip-tilt star for full multi-conjugate correction. Such a scheme overcomes a limitation of MCAO systems in which the beacons are all at a common range that leads to a requirement for three well separated tip-tilt stars [12,13]. This is the case, for example, with the Gemini South MCAO system which will use five sodium LGS [14], but will be limited in its sky coverage by the need for multiple tip-tilt stars of magnitude ~18 or brighter within 1 arc min.

MCAO is already designed as an upgrade path into LBT's LINC-NIRVANA interferometer [15], now nearing completion at the Max Planck Institute for Astronomy in Heidelberg as a collaboration between LBT's German and Italian partners. Expected to be operational in 2012, LINC-NIRVANA will extend the full resolution of the coherently combined telescope apertures down to 1.2 μm band in the near IR with resolution as high as 0.01 arc sec. To give an example of its application, at this resolution, and with LBT's enormous sensitivity, equivalent to a 12 m single aperture, stellar populations in galaxies at 5–20 Mpc will be resolved. For the first time, individual stars in giant elliptical galaxies will be within reach, allowing their star formation history to be investigated directly.

5. SUMMARY AND DISCUSSION

The LBT is now a fully operational telescope, the largest in the world, with both eyes instrumented, and with new instruments coming on line over the next three years. Later this year, the combined focus will be commissioned with the permanent installation of the LBT Interferometer and its associated imaging cameras, offering resolution at 22.7 m baseline with 110 m^2 of collecting area. AO, critical to the telescope's operation at the highest resolution, is being implemented in phases. The first ASM operating with a pyramid WFS and natural star has been shown to deliver performance that exceeds that of any other large astronomical telescope. Over the next three years, the second ASM will be deployed, the ARGOS ground-layer laser-guided system will be added, and sodium LGS will enable imaging

at the diffraction limit of resolution in the near and thermal IR over almost the entire sky. New kinds of astronomical science, particularly in studies of the very early Universe, will become feasible for the first time.

The scientific promise of the LBT with the new techniques for AO, combining multi-laser wavefront sensing with correction by adaptive secondary mirrors, is extraordinary. It will be even greater for the next generation of extremely large telescopes (ELTs) [16-18]. Indeed, the fullest scientific exploitation of these giant instruments will be required to justify their substantial cost. A key motivation for our work at the MMT telescope described here is therefore to understand how to design, build, and operate such AO systems, including ARGOS for the LBT, and in particular, systems for the 25 m Giant Magellan Telescope, where multi-LGS tomographic wavefront sensing will be essential. Because laser beacons are at finite height in the atmosphere, rays of light from LGS sample the atmosphere differently from rays of starlight. The resulting difference between wavefronts measured from a natural star and those from an LGS pointed in the same direction is called focal anisoplanatism. For 8 m telescopes, the error is not so large as to prevent high Strehl imaging in the near infrared with a single LGS, but the error grows with aperture, and for ELTs the error would be prohibitive. It can be overcome however by combining signals from multiple LGS which collectively fill the volume of atmosphere perturbing the starlight.

We note that the recent US Decadal Survey of astronomy highlights AO as a key technology for further development. AO is viewed as important to the continued exploitation of current 6.5-10 m telescopes, and no less than fundamental to the success of the Giant Segmented Mirror Telescope (GSMT). Overall, GSMT was ranked as the third priority for investment in ground-based projects, down from first place in the previous Survey in 2000. The shift in priority was described by the Committee as largely attributable to the perceived technology risk and the timeline for construction of the next generation of giant telescopes. For these reasons, investment in risk retirement by improving readiness levels for needed technologies, AO in particular, is seen as essential; federal support for GSMT is "vital to U.S. competitiveness in ground-based astronomy over the next two decades."

We are very grateful to the staffs of the LBT and the MMT for their enthusiastic support of the developmental work in AO being carried out at their facilities. Observations reported here were made at the MMT, a joint facility of the University of Arizona and the Smithsonian Institution. The work has been supported by the NSF under award AST-0505369.

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